MANURE MANAGEMENT

Optimization of Phosphorus Index and Costs of Manure Management on a New York Dairy Farm

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ABSTRACT

Manure allocation on large-scale confinement animal feeding operations is a complex management decision. This study assesses the cost effectiveness and the risk of P loss associated with various combinations of manure management options for a typical midsized dairy farm in New York State. The farm has 587 adult dairy cows (*Bos taurus*) and 430 young animals (1202 animal units). Fifty-three fields (26 cornfields and 27 pastures) ranging in size from 1 to 15 ha are available to receive livestock manure. Morgan's Soil Test P values range from 1.1 to 87.3 kg ha^{-1} (mean of 20.1 kg ha^{-1}). Options included optimal allocation of manure in time and space, surface application, incorporation, and manure storage facilities of three-, six-, and eight-month storage capacities. The decision process considered nutrient management costs (manure handling and fertilization) and the New York State P Site Index (P Index) as an indicator of one of the environmental impacts of manure management. Mathematical programming techniques and utility functions are used to select the best combination of manure management practices. The results show a convergence indicating that the best management decision would be to follow a manure allocation scheme optimized in time and space, to have three months of manure storage capacity, and to surface-apply manure. Compared with current practices, the recommended combination of practices results in an approximate 45% reduction in the mean area-weighted P Index (64.2 vs. 36.1) for a cost increase of less than 2% ($146 573 vs. $148 821).

Under the supervision of the USEPA, states are implementing new standards and permitting systems for concentrated animal feeding operations (CAFO) and animal feeding operations (AFO). This comprehensive regulatory framework means that the USEPA and individual states have a new partnership for regulating and managing livestock wastes. Arrangements for regulation will vary from state to state, but in all cases, livestock farmers have to deal with difficult decisions regarding the use or discharge of animal manures. Many of these farms work with a tiny profit margin, and new environmental restrictions regarding land manure application have heightened concern about the trade-offs between farm profitability and minimizing the risk of nonpoint nutrient losses. However, in New York State, where production agriculture is dominated by milk production, nutrient management plans (NMPs) will be used for planning fertilizer and manure applications in ways that minimize the risk of nutrient losses and maximize farm profitability.

These new and emerging institutional arrangements come in the wake of considerable organized study on manure management. After Lemunyon and Gilbert (1993), several P Indices are being developed for use as indicators of risk of P loss in runoff due to manure and fertilizer applications. These indices help planners account for environmental aspects when preparing a NMP. Although the number of factors associated with the potential for P pollution is large, planners on the ground have some incentive to work with generalized decision processes. This can mean that, in some cases, NMPs lack the sophistication needed to make environmentally correct decisions about the use of livestock wastes.

In this complex planning environment, the development of decision support systems can assist in the implementation of better management practices on farms. Management decisions can then be made or supported using as a base the solutions obtained through mathematical programming; mathematical programming models can provide a useful economic representation of the whole farm for testing various issues or policy proposals (Alocilja, 1998; Borton et al., 1995; Coote, 1973; Haith and Atkinson, 1977; Hanchar et al., 1998; Hazell and Norton, 1986).

Giasson et al. (2002) developed a manure optimization model for the purpose of developing manure management recommendations that minimize the risk of P loss resulting from manure application and the costs of manure allocation. The model is a nonlinear, nonsmooth optimization model that uses adjustable multiple-criteria optimization to assist in identifying a preferred combination of management practices through simultaneous minimization of several subfunctions. The structure of the model allows the planner to alter the relative importance of several subfunctions, making it possible to obtain solutions that meet different management objectives for manure allocation in any single-farm setting.

The objective of this study was to assess the cost effectiveness and the risk of P loss associated with various combinations of manure application methods and different sizes of manure storage facilities for a typical midsized dairy farm in New York State. Mathematical programming techniques and utility functions were used to select the best set of manure management practices.

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Published in Agron. J. 95:987–993 (2003).

Abbreviations: NMP, nutrient management plan.

METHODS AND SOURCES OF DATA

Farm Characteristics

The farm selected for this study is a dairy farm located in Cortland County, in central New York. The farm has 587 adult dairy cows and 430 young animals (1202 animal units, based on 455 kg of live weight per animal unit). The nutrient management–planning exercise was initiated based on the NMP for the 2001 crop year (defined as the period October 2000 to September 2001). Based on the NMP, a total of 53 fields are available to receive livestock manure. Field sizes range from 1 to 15 ha (mean of 5.5 ha); field distances from the barn range from 1 to 18 km (mean of 6 km); and Morgan's Soil Test P values range from 1.1 to 87.3 kg ha^{-1} (mean of 20.1 kg ha^{-1}). Of these fields, 26 are cornfields and 27 are pastures.

As defined in the farm NMP, the total volume of manure that needs to be managed is 19 044 m^3 yr^{-1}, and the nutrient content of the manure is 5.0 kg N m^{-3} (total N), 1.3 kg P_2O_5 m^{-3}, and 3.1 kg K_2O m^{-3}. The dairy manure on this farm is managed within a state-of-the-art milking facility. The current manure application method is daily surface application as the farm has no manure storage facility. The absence of a manure storage facility is not atypical in upstate New York. A recent baseline study of manure management practices showed that a significant percentage of New York's larger farms using livestock confinement systems still rely on daily spreading of livestock wastes (Poe et al., 1998).

The New York Phosphorus Index

The New York State P Index (Bryant et al., 2000), which assesses the risk of P loss from nonpoint sources on farms, is used in this study as one measure of the environmental impacts of manure management practices. The New York State P Index is similar in format to P indices developed by other states in that it includes factors that account for soil test P, additions of commercial fertilizer P or manure P, methods of P application, timing of P application, soil drainage, flooding frequency, and distance from the fields to streams. Many of these factors are weighted such that their relative importance is similar to those of P indices in neighboring states, and in agreement with neighboring states, a P Index value of 100 represents a threshold above which P-based nutrient management is mandated. Although P indices are not a direct measure of P loss, studies have shown that a P index, similar in format to the one for New York, effectively described 80% or more of the variability in measured P losses (Sharpley et al., 2001). For this planning exercise, it is important to highlight that higher P Index values indicate higher risk of P pollution, factors are multiplicative, and the method of application factors range from 0.6 for incorporation within 3 d after spreading to 1.0 for surface spreading on frozen or snow-covered ground. The timing factor for application of manure to fields is 0.4 for applications from May to August, 0.7 for applications from September to October, 0.9 for applications from November to January, and 1.0 for applications from February to April. Consequently, the ability to store manure, and thereby avoid spreading during months when the timing factor is high or when the ground is frozen or snow covered, potentially has significant effects on a yearlong P Index assessment of the risk of P loss. Although the P Index assesses individual management areas (usually one field), the goal of farm-scale NMPs is to manage nutrients to avoid nutrient management restrictions posed by high P Index values on any field or management area. For purposes of this study, optimal management is represented by the lowest possible area-weighted average P Index across all fields, thereby minimizing the environmental risk posed by any one area of the farm.

Optimization Techniques, Constraints, and Assumptions

The optimization techniques suggested by and described in Giasson et al. (2002) are used in this study, with manure management practices planned on a monthly basis to conform to required input to the P Index for the timing factor for applying manure to fields. Equal weights were used for all subfunctions in the model (mean P Index weighted by area, P Index standard deviation, and costs). Nutrient balances for crop production were taken into account in this study (Cornell Coop. Ext., 1999) as well as management constraints due to crop rotations and weather conditions pertinent to the subject farm. Restrictions on manure application for each field as recommended in the NMP were adhered to in the analyses for each scenario. For example, manure could not be applied to fields used for corn (*Zea mays* L.) production during June through September. From January to March, the soils in the region are normally snow covered, frozen, or saturated, and moldboard plowing cannot be used to incorporate manure. When applied during this period, the choice for manure application method was restricted to surface application.

The economic parameters used in this study are the same general parameters used by Giasson et al. (2002). They include the variable costs of manure handling, transport, and application in accordance with application method used, costs of fertilization, variable costs associated with manure storage, and fixed costs encountered when constructing and operating manure storage facilities. For the purposes of this analysis, manure storage facilities were assumed to have a useful life of 15 yr.

Management Scenarios

Table 1 summarizes the manure application method and storage scenarios that are evaluated and compared in this

Table 1. Summary of scenarios.

			Optimization	
Scenario	Manure application method	Storage	Spatial	Temporal
		months		
1	surficial	0	No†	Yes
2	surficial	0	Yes	Yes
3	surficial	3	Yes	Yes
4	surficial	6	Yes	Yes
5	surficial	8	Yes	Yes
6	incorporation	0	No†	Yes
7	incorporation	0	Yes	Yes
8	incorporation	3	Yes	Yes
9	incorporation	6	Yes	Yes
10	incorporation	8	Yes	Yes

† From Giasson et al. (2002).

study. Scenarios 1 and 2 were previously described and reported in the study by Giasson et al. (2002). The first of these scenarios uses the annual manure application rates for all fields (i.e., fixed in space) as they were recommended in the NMP that was developed by an expert nutrient management planner. Whereas the NMP did not specify the timing of manure applications, optimization techniques were used to determine manure allocations in time that would result in minimal costs and minimal risks of P loss (Scenario 1). In Scenario 2, manure allocation was optimized in both time and space, resulting in optimal monthly manure application rates for each field. As reported in Giasson et al. (2002), optimization techniques resulted in sizeable reductions in risks of P loss (as determined by the mean P Index for all fields weighted by area) at minimal cost. Scenarios 1 and 2 are used in this study as a baseline for comparison of the potential benefits of incorporation and manure storage.

In this study, another eight scenarios were evaluated. In Scenarios 6 and 7, the two scenarios from Giasson et al. (2002) were modified to evaluate the effects of incorporating manure in cornfields during periods of the cropping season when plowing for incorporation is feasible (i.e., October to December, April, and May). Another six scenarios (3–5 and 8–10) evaluated costs and mean P Index weighted by area assuming the availability of manure storage facilities of three different capacities and with manure either surface-applied (Scenarios 3, 4, and 5) or incorporated on cornfields when feasible (Scenarios 8, 9, and 10). In those scenarios that included storage facilities, the storage capacities considered were of sufficient size to store three, six, and eight months of manure (4644, 9444, and 12 627 m^3, respectively).

All scenarios were evaluated using optimization techniques to formulate nonlinear problems that were solved using the Premium Solver Platform version 3.5, a spreadsheet optimization program. Although this program is capable of handling up to 100 000 decision variables for nonlinear problems, factorial combinations of options considered in the scenarios evaluated in this study did approach that limit. For each scenario, model output includes recommended monthly manure application rates for each field during the crop year. Model output in the form of sets of recommendations, one set for each scenario, was summarized as the mean P Index for the farm (weighted by area across all fields) and total costs of manure handling and fertilization.

Utility Functions

To choose the best option from among the various manure storage facility scenarios, utility functions were used to allow the association and comparison of two variables having different units (i.e., mean P Index and costs). The first step for calculating the utilities of the P Index and costs associated with each farming scenario was to establish ideal points for the P Index and costs variables and determine the distance from the ideal point for the values of these variables resulting from each scenario. The ideal points for the mean area-weighted P Index and the costs were defined as the minimum values obtained in any of the evaluated scenarios. A distance function was used to calculate the linear normalized distance from the ideal point for the value of each of these variables as determined in each scenario. The distance was calculated as:

$$d_{ik}(x) = (x_{ik} - x_{ik\ \min})/(x_{ik\ \max} - x_{ik\ \min}) \quad [1]$$

where

d_{ik} = distance from the ideal point for variable i and storage capacity k ($0 \leq d_{ik} \leq 1$)

i = variable and $i = 1$ for P Index weighted by area and 2 for manure-handling and fertilization costs

k = storage capacity and $k = 0, 3, 6$, and 8, respectively, for no storage and three, six, and eight months of storage capacity

x_{ik} = value of the variable i obtained for storage capacity k

$x_{ik\ \min}$ = minimum value of the variable i obtained for storage capacity k

$x_{ik\ \max}$ = maximum value of the variable i obtained for storage capacity k

The distance from the ideal point was used to calculate the utility of each variable (u_{ik}). The reference point *utility*, in turn, is a modeling expedient used to reflect the operator's disposition toward accommodating conflicting objectives of reducing manure management costs and reducing the risk of P loss. In this study, utility is defined in a way such that distances from ideal points equal to 0 have maximum utility ($u_{ik} = 1$) and distances equal to 1 have minimum utility ($u_{ik} = 0$). The assessment of the utility function and consequently the assessment of the shape of the curve between these two points usually depend on the ranking of values of the decision-maker. Sometimes this assessment is a difficult process that has some implicit but inherent subjectivity. A linear function would mean that changes in distance from the ideal point would cause constant changes in utility although such an assumption may not be realistic. A more realistic or plausible assumption might be that a reduction in one unit of mean P Index when the farm already has a high mean P Index must carry a larger improvement in utility than a similar reduction under circumstances where the farm already has a low mean P Index. The same considerations are valid for the costs associated with manure handling and fertilization. Therefore, the use of risk-averse utility functions is appropriate (Clemen, 1995). Whereas this study is exploratory in nature, the subjectivity associated with a choice of the shape of the utility curve is avoided. Rather, several combinations of utility functions for mean P Index and cost are incorporated into this analysis. The utility functions used for calculating utilities for the variables are (i) $u_{ik} = 1 - d_{ik}$, (ii) $u_{ik} = 1 - d_{ik}^{0.5e}$, (iii) $u_{ik} = 1 - d_{ik}^{e}$, (iv) $u_{ik} = 1 - d_{ik}^{1.5e}$, and (v) $u_{ik} = 1 - d_{ik}^{2e}$. The utility functions iii, iv, and v are used for determining mean P Index utility. Utility functions i, ii, iii, and iv are used for calculating cost utility.

The individual utilities of the mean P Index weighted by area and of the cost must be combined to define the final utility of each management strategy. In making these combinations to define the final utility, different weights may be assigned for the utilities of the P Index and the cost. The model is solved for several interactions using alternative assumptions for evaluating the presumed relations between managing nutrients and farm profitability. Specifically, the possibility that controlling nutrients might be doubly important relative to manure management costs is evaluated using a double area-weighted P Index utility (2:1). The cases for assigning equal importance for both utilities (1:1) and for assigning double importance for cost utility (1:2) are also evaluated. The utility of each scenario was calculated as:

$$U_k = \frac{w_1 \times u_{1k} + w_2 \times u_{2k}}{w_1 + w_2} \quad [2]$$

where U_k = total utility when using storage capacity k, u_{1k} = utility of mean P Index weighted by area when using storage capacity k, u_{2k} = cost utility when using storage capacity k, and w_1 and w_2 = weights assigned to u_{1k} and u_{2k}, respectively.

Table 2. Mean area-weighted P Index for the 10 scenarios combining manure storage sizes and methods of manure application ($p < 0.05$).

Storage capacity	Schedule and rates	Surficial application	Incorporation	Mean
months		P Index		
0	NMP† plan	64.2‡ (1)§	60.5 (6)	62.4a¶
0	Optimized	44.8‡ (2)	44.4 (7)	44.6b
3	Optimized	36.1 (3)	33.9 (8)	35.0c
6	Optimized	33.9 (4)	30.2 (9)	32.1c
8	Optimized	31.7 (5)	28.9 (10)	30.3c
Mean		42.1A	39.6A	

† NMP, nutrient management plan.
‡ Results from Giasson et al. (2002).
§ Numbers in parentheses indicate the scenario number.
¶ Lowercase letters are comparisons among means for different storage capacities, and uppercase letters are comparisons among means of scenarios with manure incorporated and manure surface-applied.

RESULTS AND DISCUSSION

Summarized results for each of the scenarios described in the previous section are shown in Tables 2 and 3. Values for mean area-weighted P Index (Table 2) and total nutrient management costs (i.e., manure-handling and application costs plus the cost of supplemental commercial fertilization, if needed; Table 3) are given.

Cost–Benefit Analysis

Table 2 shows that application rates in accordance with the NMP (Scenario 1) were not completely optimized in space. Using the mathematical programming approach to optimize manure spreading in both time and space (Scenario 2) resulted in a reduction of the mean area-weighted P Index of 19.4 units (30% reduction) when application method is restricted to surface application, as is currently practiced on this farm. The slight increase in cost (Scenario 1 vs. 2, Table 3) is due to the recommendation, derived by optimization techniques, to apply more manure in fields that are located at larger distances from the barn (Giasson et al., 2002). Clearly, the best cost–benefit ratio results from optimal management of manure applications in space and time.

Adopting the practice of manure storage using any of the three different-sized storage facilities provides an additional (approximately 25%) reduction in the mean area-weighted P Index (Scenario 2 vs. 3–5, Table 2). For the same comparisons, the cost increases are less than 5% (Table 3). However, the incremental reductions in mean area-weighted P Index that result from increasing storage capacity from three months to six or eight months are only 8 and 13%, respectively, and increased costs are not insignificant.

Compared with the benefits and costs of optimizing manure applications and adopting the practice of manure storage, the proportional reduction in the mean area-weighted P Index due to incorporation of manure is approximately 6%, whereas the cost increases range from 10 to 25%. Consequently, adopting manure storage is much more cost effective than manure incorporation. The small reduction in the mean weighted P Index derived from manure incorporation is due to the fact that incorporation is restricted to just a few months on cornfields due to crop and weather restrictions. Incorporation does appear more effective in reducing the mean P Index when in combination with larger storage capacities. This is because more manure can be stored for application in May, which, according to the New York State P Index, is a month when manure applications have the smallest pollution potential.

Figures 1 and 2 show the continuous function relationships between storage capacity and P Index and between storage capacity and total costs, respectively. The values for zero storage capacity are for the optimized scenarios (2 and 7). The continuous reduction in the mean P Index with increase in the storage capacity occurs because greater storage capacity allows management to avoid manure applications during months when the potential risk of P transport to waters is greater. Three months of storage allows for avoiding manure applications from February through April, six months of storage allows for avoiding manure application from November to April, and eight months of storage makes it possible to avoid manure application from September to April. As

Table 3. Total cost of manure handling and fertilization for the 10 scenarios combining manure storage sizes and methods of manure application ($p < 0.05$).

Storage capacity	Schedule and rates	Surficial application	Incorporation	Mean
months		Costs, US$		
0	NMP† plan	146 573‡ (1)	161 760 (6)§	155 289a¶
0	Optimized	147 761‡ (2)	165 061 (7)	156 411a
3	Optimized	148 821 (3)	168 000 (8)	158 410a
6	Optimized	151 700 (4)	189 519 (9)	170 609a
8	Optimized	154 910 (5)	194 947 (10)	174 929a
Mean		149 953B	175 857A	

† NMP, nutrient management plan.
‡ Results form Giasson et al. (2002).
§ Numbers in parentheses indicate the scenario number.
¶ Lowercase letters are comparisons among means for different storage capacities, and uppercase letters are comparisons among means of scenarios with manure incorporated and manure surface-applied.

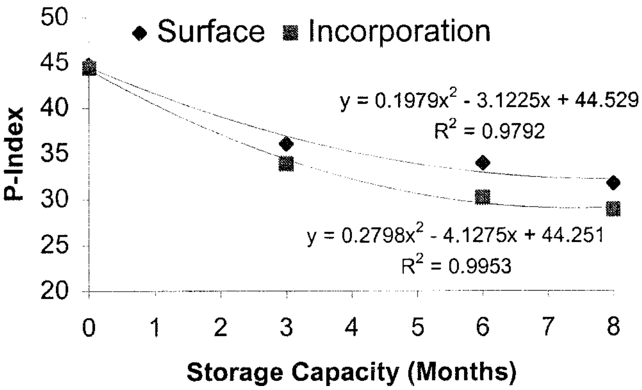

Fig. 1. Reduction of the mean weighted P Index as a function of storage capacity.

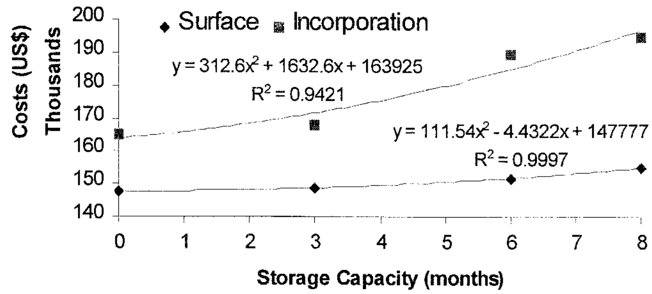

Fig. 2. Increase in costs of manure handling and fertilization as a function of storage capacity.

previously described, the timing factor in the P Index is higher during periods when average climate conditions result in increased risk of P transport.

Utility Function Analyses

Given that the two variables representing benefits and costs have different units, utility functions were used to choose a preferred option. Because the results show that manure incorporation is not very cost effective as a means of lowering the mean weighted P Index, surface manure application was considered a better management choice. Therefore, only surface application is considered in the utility analysis (Scenarios 2–5). For these four scenarios, Table 4 presents the distance from the ideal point and the utilities for mean area-weighted P Index and for cost. Tables 5, 6, and 7 present the final utility values for each storage facility and for each combination of utility functions for mean P Index and cost. In Table 5, P Index utility (2:1) is given double importance; in Table 6, both utilities have the same importance (1:1); and in Table 7, double importance is given to cost utility (1:2). Bold numbers indicate the best storage capacity for each combination of utility functions.

The results in Tables 5, 6, and 7 show a convergence to the recommendation of three months of manure storage capacity. The best solution would be six months of storage capacity only when mean P Index weighted by area utility has double importance and with a mean P Index utility function $u = 1 - d^e$. However, the combination of double importance for mean P Index utility and a smaller factor multiplying e in the exponential utility function is somewhat inconsistent. For all other combinations of utility functions and different weights for mean P Index and costs utilities, there is a convergence indicating that three months of storage capacity would be the best choice for this farm.

If one would define the utility functions based on specific nutrient management and economic objectives, then a single best option would result. However, the nature of this solution would be directly associated with the shape of the utility functions and weighting of the variables. Frequently, the process of defining specific nutrient management and economic objectives has intrinsic subjectivity. Any disagreement with these specifically defined objectives would mean no confidence in the fitness of the best solution. The use of the procedure adopted here and the calculation of several utility values is a way to avoid the subjectivity of defining specific utility functions. Although multiple best solutions were found, it was discovered that there was a convergence among these solutions and that a global best solution could be found while avoiding the subjectivity inherent to the assessment of personal values. The global best management decision would be allocating manure following the manure allocation scheme with time and rates of manure application optimized, surface applying manure, and having a manure storage facility with three months storage capacity.

CONCLUSIONS

The optimization techniques used in this study are demonstrably effective for evaluating alternative farm scenarios for manure and nutrient management. Dealing with trade-offs between nutrient management and manure-handling costs with this level of sophistication may pave the way for more precise determinations of

Table 4. Distance from ideal point and utilities (optimized surface manure application and storage options, Scenarios 2–5) for P Index weighted by area and for total cost using several utility functions.

			Utility†				
	Storage	Distance	$u = 1 - d$	$u = 1 - d^{0.5e}$	$u = 1 - d^e$	$u = 1 - d^{1.5e}$	$u = 1 - d^{2e}$
P Index	**0**	**1.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
	3	**0.59**	**0.41**	**0.52**	**0.77**	**0.89**	**0.95**
	6	**0.22**	**0.78**	**0.87**	**0.98**	**1.00**	**1.00**
	8	**0.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
Cost	**0**	**0.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
	3	**0.37**	**0.63**	**0.74**	**0.93**	**0.98**	**1.00**
	6	**0.75**	**0.25**	**0.33**	**0.55**	**0.70**	**0.80**
	8	**1.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**

† u = utility; d = distance from ideal point.

Table 5. Total utility values when mean P Index weighted by area utility has double importance (2:1).

P Index utility function	Storage	Cost utility function†			
		$u = 1 - d$	$u = 1 - d^{0.5e}$	$u = 1 - d^{e}$	$u = 1 - d^{1.5e}$
	months				
$u = 1 - d^{e}$	0	0.33	0.33	0.33	0.33
	3	0.72	0.76	0.82	0.84
	6	*0.74*‡	*0.77*	*0.84*	*0.89*
	8	0.67	0.67	0.67	0.67
$u = 1 - d^{1.5e}$	0	0.33	0.33	0.33	0.33
	3	*0.80*	*0.84*	*0.90*	*0.92*
	6	0.75	0.77	0.85	0.90
	8	0.67	0.67	0.67	0.67
$u = 1 - d^{2e}$	0	0.33	0.33	0.33	0.33
	3	*0.84*	*0.88*	*0.94*	*0.96*
	6	0.75	0.78	0.85	0.90
	8	0.67	0.67	0.67	0.67

† u = utility; d = distance from ideal point.
‡ Italic values indicate the storage capacity with higher utility for each combination of utility functions.

Table 6. Total utility values when mean P Index weighted by area utility and cost have the same importance (1:1).

P Index utility function	Storage	Cost utility function†			
		$u = 1 - d$	$u = 1 - d^{0.5e}$	$u = 1 - d^{e}$	$u = 1 - d^{1.5e}$
	months				
$u = 1 - d^{e}$	0	0.50	0.50	0.50	0.50
	3	*0.70*‡	*0.75*	*0.85*	*0.87*
	6	0.62	0.66	0.77	0.84
	8	0.50	0.50	0.50	0.50
$u = 1 - d^{1.5e}$	0	0.50	0.50	0.50	0.50
	3	*0.76*	*0.81*	*0.91*	*0.93*
	6	0.63	0.66	0.77	0.85
	8	0.50	0.50	0.50	0.50
$u = 1 - d^{2e}$	0	0.50	0.50	0.50	0.50
	3	*0.79*	*0.84*	*0.94*	*0.96*
	6	0.63	0.66	0.77	0.85
	8	0.50	0.50	0.50	0.50

† u = utility; d = distance from ideal point.
‡ Italic values indicate the storage capacity with higher utility for each combination of utility functions.

Table 7. Total utility values when cost is more important than mean P Index weighted by area utility (1:2).

P Index utility function	Storage	Cost utility function†			
		$u = 1 - d$	$u = 1 - d^{0.5e}$	$u = 1 - d^{e}$	$u = 1 - d^{1.5e}$
	months				
$u = 1 - d^{e}$	0	0.67	0.67	0.67	0.67
	3	*0.68*‡	*0.75*	*0.88*	*0.91*
	6	0.50	0.55	0.69	0.79
	8	0.33	0.33	0.33	0.33
$u = 1 - d^{1.5e}$	0	0.67	0.67	0.67	0.67
	3	*0.72*	*0.79*	*0.92*	*0.95*
	6	0.50	0.55	0.70	0.80
	8	0.33	0.33	0.33	0.33
$u = 1 - d^{2e}$	0	0.67	0.67	0.67	0.67
	3	*0.74*	*0.81*	*0.94*	*0.97*
	6	0.50	0.55	0.70	0.80
	8	0.33	0.33	0.33	0.33

† u = utility; d = distance from ideal point.
‡ Italic values indicate the storage capacity with higher utility for each combination of utility functions.

best manure management practices at the farm level. For the subject farm used in this analysis, the best management option is improved manure allocation in time and space and a manure storage facility with three months of storage capacity. Compared with current practices, the recommended combination of practices would result in an approximate 45% reduction in the mean area-weighted P Index (64.2 vs. 36.1) for a cost increase of less than 2% ($146 573 vs. $148 821).

Incorporation of manure as a specific practice for reducing the risk of P loss is not cost effective compared with other options, but that does not preclude incorporation when tillage is required for other reasons as part of normal farming practices. Manure storage increases the potential for incorporation during normal fall or spring tillage operations, which would provide additional environmental benefits. The magnitude of these accessory benefits was not assessed in this study.

Currently, the manure and nutrient management issue being addressed by P indices relates to water quality. However, many other environmental considerations are in play. Nitrogen and pathogens also pose a threat to water quality. When manure is surface-applied, air quality can be affected by odors. Increases in insect populations can become an issue as well. Increasingly, these aspects of manure management are becoming important environmental and social problems. Therefore, further research that would make a more thorough accounting of waste management issues on the farm should include these other variables. To address these issues, utility functions that account for these aspects could possibly be incorporated into the decision-making process using the same optimization techniques used in this study.

ACKNOWLEDGMENTS

CAPES (Brazilian Federal Agency for Post-Graduate Education, Brasília, Brazil) and Cornell University Agricultural Experiment Station provided financial support. George Bullin and Greg Albrecht provided the farm data.

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